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Application of multi-criteria decision making to sustainable energy planning—A review

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Abstract

Multi-Criteria Decision Making (MCDM) techniques are gaining popularity in sustainable energy management. The techniques provide solutions to the problems involving conflicting and multiple objectives. Several methods based on weighted averages, priority setting, outranking, fuzzy principles and their combinations are employed for energy planning decisions. A review of more than 90 published papers is presented here to analyze the applicability of various methods discussed. A classification on application areas and the year of application is presented to highlight the trends. It is observed that Analytical Hierarchy Process is the most popular technique followed by outranking techniques PROMETHEE and ELECTRE. Validation of results with multiple methods, development of interactive decision support systems and application of fuzzy methods to tackle uncertainties in the data is observed in the published literature.

Keywords: Multi-objective optimization; Multi-criteria decision making; Decision support systems; Sustainable energy planning

Contents

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1. Introduction

Energy planning using multi-criteria analysis has attracted the attention of decision makers for a long time. The methods can provide solutions to increasing complex energy management problems. Traditional single criteria decision making is normally aimed at maximization of benefits with minimization of costs. These methods provide better understanding of inherent features of decision problem, promote the role of participants in decision making processes, facilitate compromise and collective decisions and provide a good platform to understanding the perception of models' and analysts' in a realistic scenario. The methods help to improve quality of decisions by making them more explicit, rational and efficient. Negotiating, quantifying and communicating the priorities are also facilitated with the use of these methods.

During the 1970s, energy planning efforts were directed primarily towards energy models aimed at exploring the energy–economy relationships established in the energy sector. The main objectives followed were to accurately estimate future energy demand. A single criteria approach aimed at identifying the most efficient supply options at a low cost was popular [1,2]. In the 1980s, growing environmental awareness has slightly modified the above decision framework [3]. The need to incorporate environmental and social considerations in energy planning resulted in the increasing use of multicriteria approaches.

Multi-objective linear programming is another planning methodology used for illustrating the trade-off between environmental and economic parameters and for assisting in the selection of a compromise solution [4,5]. It was popular in energy planning with conventional fuels in the 1970s. However, after the oil shock of 1973, a thought was given for energy conservation and energy substitution. Renewable energy sources are being promoted for a wide variety of applications worldwide. They are free from any form of pollution and are capable of substituting for

conventional fuels in most of the applications. However, the contribution of these sources is very low, despite considerable technological development and their increasing competitiveness with respect to conventional fuels. This compels the planners and decision makers to identify the barriers for penetration and suggest interventions to overcome them. It is therefore felt that, along with the necessary policy measures, the wide exploitation of sustainable energy should be based on a completely different conception of energy planning procedure. The role of different actors in decision making thus becomes important. Methods of group decision are therefore of primary interest for the implementation of decision sciences in real-life problems.

Multi-criteria decision making (MCDM) methods deal with the process of making decisions in the presence of multiple objectives. A decision-maker is required to choose among quantifiable or non-quantifiable and multiple criteria. The objectives are usually conflicting and therefore, the solution is highly dependent on the preferences of the decision-maker and must be a compromise. In most of the cases, different groups of decision-makers are involved in the process. Each group brings along different criteria and points of view, which must be resolved within a framework of understanding and mutual compromise. Applications of MCDM include areas such as integrated manufacturing systems [6], evaluations of technology investment [7], water and agriculture management [8,9] in addition to energy planning [10–12].

2. Overview of multi-criteria decision making (MCDM) methods

Multi-Criteria Decision Making is a well known branch of decision making. It is a branch of a general class of operations research models which deal with decision problems under the presence of a number of decision criteria. This major class of models is very often called MCDM. This class is further divided into multi-objective decision making (MODM) and multi-attribute decision making (MADM) [13]. There are several methods in each of the above categories. Priority based, outranking, distance based and mixed methods are also applied to various problems. Each method has its own characteristics and the methods can also be classified as deterministic, stochastic and fuzzy methods. There may be combinations of the above methods. Depending upon the number of decision makers, the methods can be classified as single or group decision making methods. Decision making under uncertainty and decision support systems are also prominent decision making techniques [14].

These methodologies share common characteristics of conflict among criteria, incomparable units, and difficulties in selection of alternatives. In multiple objective decision making, the alternatives are not predetermined but instead a set of objective functions is optimized subject to a set of constraints. The most satisfactory and efficient solution is sought. In this identified efficient solution it is not possible to improve the performance of any objective without degrading the performance of at least one other objective. In multiple attribute decision making, a

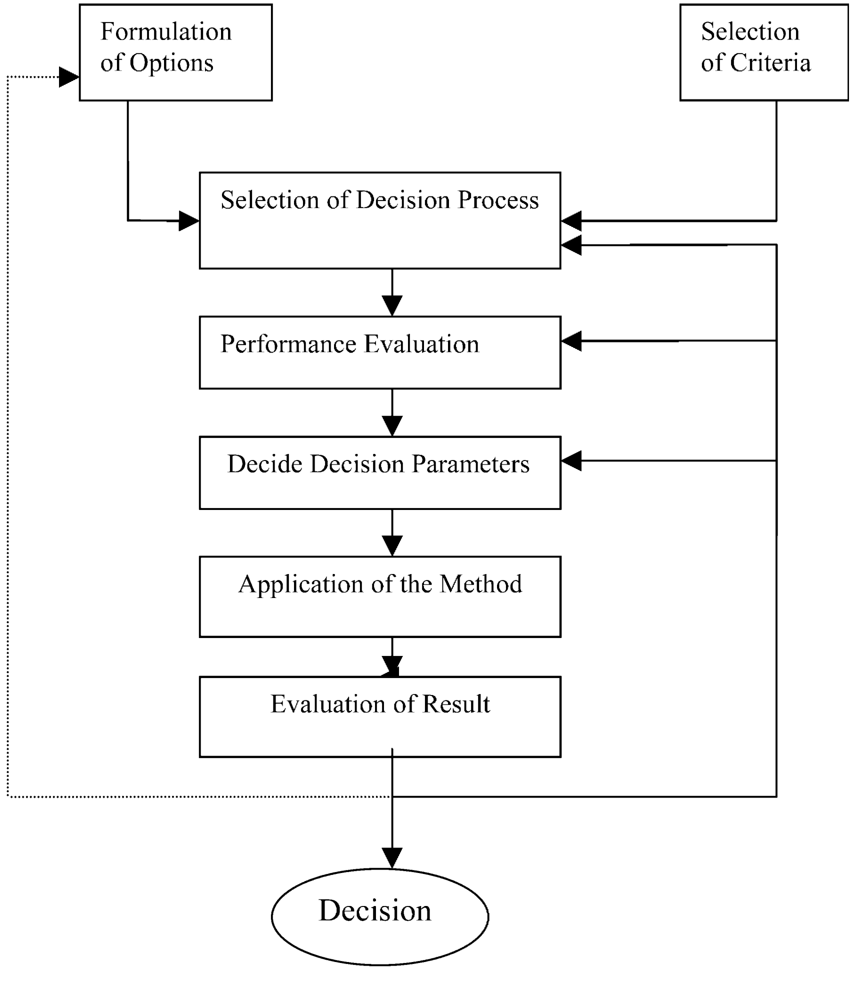


Fig. 1. Multicriteria decision process.

small number of alternatives are to be evaluated against a set of attributes which are often hard to quantify. The best alternative is usually selected by making comparisons between alternatives with respect to each attribute. The multicriteria decision process is as shown in Fig. 1. The different methods are described as follows.

2.1. Weighted sum method (WSM)

The WSM is the most commonly used approach, especially in single dimensional problems. If there are M alternatives and N criteria then the best alternative is the

one that satisfies the following expression:

$$A^{*}_{WSM} = Max\sum_{i}^{j} a_{ij}w_j \quad \text{for} \quad i = 1, 2, 3, ...M \tag{1}$$

where A^{*}_{WSM} is the WSM score of the best alternative, N is the number of decision criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion. The total value of each alternative is equal to the sum of products. Difficulty with this method emerges when it is applied to multi-dimensional decision-making problems. In combining different dimensions, and consequently different units, the additive utility assumption is violated [15].

2.2. Weighted product method (WPM)

The WPM is very similar to WSM. The main difference is that instead of addition in the model there is multiplication. Each alternative is compared with the others by multiplying a number of ratios, one for each criterion. Each ratio is raised to the power equivalent to the relative weight of the corresponding criterion. In general, in order to compare the alternatives A_K and A_L the following product is obtained:

$$R(A_K/A_L) = \sum_{j=1}^{N} (a_{kj}/a_{Lj})^{w_j} \tag{2}$$

where N is the number of criteria, a_{ij} is the actual value of the i^{th} alternative in terms of the j^{th} criterion, and w_j is the weight of importance of the j^{th} criterion. If $R\ (A_K/A_L)$ is greater than one, then alternative A_K is more desirable than alternative A_L (in the maximization case). The best alternative is the one that is better than or at least equal to all the other alternatives [16].

2.3. Analytical hierarchy process (AHP)

Analytical Hierarchy Process (AHP) is developed by Saaty [17,18]. The essence of the process is decomposition of a complex problem into a hierarchy with goal (objective) at the top of the hierarchy, criterions and sub-criterions at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy. Elements at given hierarchy level are compared in pairs to assess their relative preference with respect to each of the elements at the next higher level. The verbal terms of the Saaty's fundamental scale of 1–9 is used to assess the intensity of preference between two elements. The value of 1 indicates equal importance, 3 moderately more, 5 strongly more, 7 very strongly and 9 indicates extremely more importance. The values of 2, 4, 6, and 8 are allotted to indicate compromise values of importance. Ratio scale and the use of verbal comparisons are used for weighting of quantifiable and non-quantifiable elements. The method computes and aggregates their eigenvectors until the composite final vector of weight coefficients for alternatives is obtained. The entries of final weight coefficients vector reflect the

relative importance (value) of each alternative with respect to the goal stated at the top of hierarchy. A decision maker may use this vector due to his particular needs and interests. To elicit pair wise comparisons performed at a given level, a matrix A is created in turn by putting the result of pair wise comparison of element i with element j into the position a_{ji} as below.

$$A = \begin{bmatrix} a_{11} & a_{12} & . & a_{1n} \\ a_{21} & a_{21} & . & a_{2n} \\ a_{n1} & a_{n2} & . & a_{nn} \end{bmatrix} \tag{3}$$

After obtaining the weight vector, it is then multiplied with the weight coefficient of the element at a higher level (that was used as criterion for pair wise comparisons). The procedure is repeated upward for each level, until the top of the hierarchy is reached. The overall weight coefficient, with respect to goal for each decision alternative is then obtained. The alternative with the highest weight coefficient value should be taken as the best alternative. One of the major advantages of AHP is that it calculates the inconsistency index as a ratio of the decision maker's inconsistency and randomly generated index. This index is important for the decision maker to assure him that his judgments were consistent and that the final decision is made well. The inconsistency index should be lower than 0.10. Although a higher value of inconsistency index requires re-evaluation of pair wise comparisons, decisions obtained in certain cases could also be taken as the best alternative.

2.4. Preference ranking organization method for enrichment evaluation (PROMETHEE)

This method uses the outranking principle to rank the alternatives, combined with the ease of use and decreased complexity. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. Brans et al. [19] have offered six generalized criteria functions for reference namely, usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion. The method uses preference function $P_j\ (a,\ b)$ which is a function of the difference d_j between two alternatives for any criterion j, i. e. $d_j = f(a,\ j) - f(b,\ j)$, where $f(a,\ j)$ and $f(b,\ j)$ are values of two alternatives a and b for criterion j. The indifference and preference thresholds q' and p' are also defined depending upon the type of criterion function. Two alternatives are indifferent for criterion j as long as d_j does not exceed the indifference threshold q'. If d_j becomes greater than p', there is a strict preference. Multi-criteria preference index, $\pi(a, b)$ a weighted average of the

preference functions $P_j\ (a, b)$ for all the criteria is defined as

$$\pi(a,b) = \frac{\sum_{j=1}^{J} w_j P_j(a,b)}{\sum_{j=1}^{J} w_j} \tag{4}$$

$$\phi^+(a) = \sum_A \pi(a,b) \tag{5}$$

$$\phi^-(a) = \sum_A \pi(b,a) \tag{6}$$

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{7}$$

where w_j is the weight assigned to the criterion j; $\phi^+(a)$ is the outranking index of a in the alternative set A; $\phi^-(a)$ is the outranked index of a in the alternative set A; $\phi(a)$ is the net ranking of a in the alternative set A. The value having maximum $\phi(a)$ is considered as the best.

$$a \text{ outranks } b \text{ iff } \phi(a) > \phi(b), a \text{ is indifferent to } b \text{ iff } \phi(a) = \phi(b)$$

2.5. The elimination and choice translating reality (ELECTRE)

This method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives. The problem is to be so formulated that it chooses alternatives that are preferred over most of the criteria and that do not cause an unacceptable level of discontent for any of the criteria. The concordance, discordance indices and threshold values are used in this technique. Based on these indices, graphs for strong and weak relationships are developed. These graphs are used in an iterative procedure to obtain the ranking of alternatives [20]. This index is defined in the range (0–1), provides a judgment on degree of credibility of each outranking relation and represents a test to verify the performance of each alternative. The index of global concordance C_{ik} represents the amount of evidence to support the concordance among all criteria, under the hypothesis that A_i outranks A_k. It is defined as follows.

$$C_{ik} = \sum_{j=1}^{m} W_j c_j(A_i A_k) / \sum_{j=1}^{m} W_j \tag{8}$$

where W_j is the weight associated with j^{th} criteria. Finally, the ELECTRE method yields a whole system of binary outranking relations between the alternatives. Because the system is not necessarily complete, the ELECTRE method is sometimes unable to identify the preferred alternative. It only produces a core of leading alternatives. This method has a clearer view of alternatives by eliminating less favorable ones, especially convenient while encountering a few criteria with a large number of alternatives in a decision making problem [21].

2.6. The technique for order preference by similarity to ideal solutions (TOPSIS)

This method is developed by Huang and Yoon [22] as an alternative to ELECTRE. The basic concept of this method is that the selected alternative should have the shortest distance from the negative ideal solution in geometrical sense. The method assumes that each attribute has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions. Thus, the preference order of alternatives is yielded through comparing the Euclidean distances. A decision matrix of M alternatives and N criteria is formulated firstly. The normalized decision matrix and construction of the weighted decision matrix is carried out. This is followed by the ideal and negative-ideal solutions. For benefit criteria the decision maker wants to have maximum value among the alternatives and for cost criteria he wants minimum values amongst alternatives. This is followed by separation measure and calculating relative closeness to the ideal solution. The best alternative is one which has the shortest distance to the ideal solution and longest distance to negative ideal solution.

2.7. Compromise programming (CP)

Compromise Programming defines the best solution as the one in the set of efficient solutions whose point is the least distance from an ideal point [23].The aim is to obtain a solution that is as close as possible to ideal. The distance measure used in CP is the family of L_p-metrics and is given as

$$L_p(a) = \sum_{j=1}^{j} w_j^p \left| f_j^* - f(a) \right| / \left| M_j - m_j \right| \tag{9}$$

where L_p (a) is the L_p metric for alternative a, f (a) is the value of criterion j for alternative a, M_j is the maximum (ideal) value of criterion j in set A, m_j is the minimum (anti ideal) value of criterion j in set A, f_j^* is the ideal value of criterion j, w_j is the weight of the criterion j, p is the parameter reflecting the attitude of the decision maker with respect to compensation between deviations. For $p = 1$, all deviations from f_j* are taken into account in direct proportion to their magnitudes meaning that there is full (weighted) compensation between deviations

2.8. Multi-attribute utility theory (MAUT)

Multi-attribute Utility Theory takes into consideration the decision maker's preferences in the form of the utility function which is defined over a set of attributes The utility value can be determined by determination of single attribute utility functions followed by verification of preferential and utility independent conditions and derivation of multi-attribute utility functions. The utility functions can be either additively separable or multiplicatively separable with respect to single attribute utility. The multiplicative form of equation for then utility value is defined as

follows.

$$1 + ku(x_1, x_2, \ldots x_n) = \prod_{j=1}^{n}(1 + kk_j u_j(x_j)) \tag{10}$$

Here j is the index of attribute, k is overall scaling constant (greater than or equal to -1), k_j is the scaling constant for attribute j, $u(.)$ is the overall utility function operator, $u_j(.)$ is the utility function operator for each attribute j [24].

3. Multi-criteria decision making applications in energy planning

The application areas of MCDM in energy planning presented in this section are renewable energy planning, energy resource allocation, building energy management, transportation energy management, planning for energy projects, electric utility planning and other miscellaneous areas. The comparison of MCDM methods applicable to energy planning are discussed in the literature. Hobbs and Meirer [25] compared the methods with respect to simplicity of applications and feasible expected outcomes, Huang and Poh [26] discussed the methods used in energy and environmental modeling under uncertainties, Lahdelma et al. [27] discussed these methods for environmental planning and management. The commonly applied MCDM methods out of the above are multi-objective optimization, AHP, PROMETHEE, ELECTRE, MAUT, fuzzy methods and decision support systems (DSS). More than one MCDM method is also applied in many application areas to validate the results [28–30].

A review of the published literature is presented here with a view to highlighting the applications areas and trends. A classification of published literature before 1990 and beyond 1990 is also presented to highlight suitability of the methods in changed global scenario. Six generalized application areas and a miscellaneous area presented here have common features of minimization of cost benefit ratios, high degrees of uncertainties in formulating the problems, incommensurable units and the need to handle socio-economic aspects in planning. Renewable energy planning and energy resource allocation refers to compilation of feasible energy plan and dissemination of various renewable energy options. The key factors applicable are investment planning, energy capacity expansion planning and evaluation of alternative energies. Building energy management refers to design, selection, installation and building energy management options in a multi-criteria environment. The application normally deals with quantitative issues. Transportation system applications include evaluation of alternative strategies for pollution control, elimination of old polluting vehicles, choosing between private and public transport etc. The key features of transportation applications are of a high concern for socio-economic reasons. Project planning refers to site selection, technology selection and decision support in renewable energy harnessing projects. The objectives are arriving at a Pareto optimal solution for technology selection, sizing, execution, investment planning. Optimal electrical dispatch scheduling, deciding power generation mix, optimum electricity supply planning are the applications of electric utility

planning using MCDM. Miscellaneous applications include desalination plant selection, solid waste management.

It can be observed from the surveyed literature that AHP is the most popular method for prioritizing the alternatives, followed by PROMETHEE and ELECTRE. Multi-objective programming is also very widely used to formulate alternative plans. Fuzzy MCDM methods are also adopted for considering the uncertainties in energy planning. Decision support systems are becoming popular in energy planning and resource allocation with the advent of the latest computational aids.

3.1. Multi-objective optimization

This method is very widely used in energy resource allocation, energy planning and electric utility applications. Maximization of cost benefit ratio to arrive at optimum resource allocation in rural areas [31], national level energy planning [32] are amongst a few applications. The application areas have common features of higher investment costs, higher project durations, conflicting objectives and uncertainty. Energy security and social benefits are prominent objectives in energy planning with these methods. These techniques are also used for sustainability evaluation of power plants [33], deciding optimum mix of renewable energy technologies at various sectors [34–37]. Renewable energy planning with energy environment linkages [38], economic constraints, technology limitations etc. are the main features of applications surveyed . Applications to various national level issues [39–42] and household energy issues [43,44] are also among the prominent application areas. Multi-objective optimization also finds applications in building energy management [45]. The issues identified are building material design [46], building performance design [47,48], building arrangement design [49], and building shape design [50,51]. Regional energy supply optimization [52,53], desalination power plant selection [54,55], electricity distribution planning using fuzzy approaches [56,57] are also worth mentioning. Genetic algorithms are also applied to electric utility planning and building energy management problems [46]. An analysis of utilizing multi-objective optimization reveals that the methods are being used for a wide variety of applications after 1990. These may be due to the advent of sophisticated computational aids available and increased need for larger socio-economic considerations in energy planning.

3.2. Decision Support System (DSS)

These are sophisticated, interactive and computer aided techniques for aiding the decisions [58]. These can support complex problems that would be otherwise difficult to handle. Knowledge based DSS can support the decision makers in selecting criteria, alternatives and trade-offs, thus making the energy planning simple. The identified DSS use MCDM methods for arriving at interim results. The applications of DSS in energy planning developed are solid waste management [59], transportation energy management [60], electricity production alternatives [61], building energy management [62] and renewable energy project planning [63].

3.3. Multi-criteria decision making methods

The Multi Attribute Utility Theory is developed to help decision makers assign utility values to outcomes by evaluating these in terms of multiple attributes and combining individual assignments to obtain overall utility values. It is observed that MAUT is not very extensively used in energy planning. This may be due to requirements of interactive decision environment required in formulating utility functions, complexity of computing scaling constants using the algorithm [64]. Selecting portfolios for solar energy projects [65], energy policy making [66], environmental impact assessment [67] and electric power system expansion planning [68] are the applications identified in the literature. A few numbers of studies are observed using this method after 1990.

The outranking methods belonging to ELECTRE family are popularly used in energy planning. These methods are also used in renewable energy DSS after 1990 [62,69,70].Other common application areas include electric utility planning, building energy management and project planning. These methods are also applied to selection of thermal power plant location by eliminating certain sites [71], renewable energy plant selection [72,73], selecting pollution control technologies [74] and transportation energy planning [75,76]. Though various versions of ELECTRE are developed ELECTRE III is found to be widely used in energy planning applications.

Outranking methods belonging to PROMETHEE category are also extensively used in energy planning. These methods provide a scientific basis to arrive at multi-criteria preference index by calculating the strengths and weaknesses of alternative actions. This method is used in energy project planning and applications to geothermal site selection [77,78] and small hydro site selections [79]. Other application areas are impact analysis of energy alternatives [80,81], old vehicle elimination [75,76] and building product designs [82]. Different versions of PROMETHEE are in use and PROMETHEE II has been extensively used after 1990.

Analytical Hierarchy Process is very widely used in energy planning. This may be due to provisions of converting a complex problem into a simple hierarchy, flexibility, intuitive appeal, its ability to mix qualitative as well as quantitative criteria in the same decision framework [83] and use of computational aids leading to successful decisions in many domains [84]. Though a there are number of shortcomings [85], the method is popularly used in renewable energy planning [86–90], energy resource allocation [91], transportation energy planning [92], project planning [93] and electric utility planning [94–96]. The applications surveyed have the main objectives of priority setting and have features such as less number of criteria, interaction with decision makers etc. The correctness of AHP has been established by comparing it with other MCDM methods. The method is used with modifications during post 1990.

In addition to the above discussed methods, preference desegregation method is also used for energy analysis and policy making studies [97]. Fuzzy set programming is used for a variety of applications after 1990. A few of the application areas surveyed are solar system evaluation [98,99], power systems [100–103] and wind site selection [104].

Table 1
Classification of MCDM methods by application areas

Applications	Multi-objective	Methods					Total number
		MAUT	AHP	PROMETHEE	ELECTRE	Others	
Renewable energy planning	[2,33–38]	[65,66]	[87,90,95,96]	[70,75,79]	[69,70]	[62,97–99,104]	***22***
Energy resource allocation	[43,88,89,95]		[88–91]			[1–32,39]	***10***
Building energy management	[46,47,49–51]			[82]	[45,62]		***8***
Transportation energy systems			[76,92]	[76]	[75]	[60]	***5***
Project planning			[93]	[77,78]	[71–74]		***7***
Electric utility planning	[4,5,53,101]	[67,68]	[94–96]			[59,98,100,102]	***12***
Others	[56]				[74]		***2i***
Total number	***22***	***4***	***14***	***7***	***10***	***13***	

Numbers in square brackets refer to reference numbers.

Table 2
Classification of MCDM methods by year of publication

Year of Publication	Upto 1990	Beyond 1990	Total Number
Multi-Objective	[2,4,5,40,47,53,89]	[25,33–38,43,46,49–51,56,95,101]	***22***
MAUT	[65,66]	[67,68]	***4***
AHP	[75,76,94]	[87–93,95,96]	***14***
PROMETHEE	[75,76,79]	[70,77,78,82]	***7***
ELECTRE	[71,79]	[45,62,69,70,72–75]	***10***
Others	[31,32]	[25,39,59–60,62,97]–100, 102,104]	***13***
Total Number	***19***	***48***	

Numbers in square brackets refer to reference numbers.

It can be observed from the studies (Tables 1 and 2) that multi-objective optimization accounts for 29% of the identified studies, followed by AHP (20%), ELECTRE (15%), PROMETHEE (10%). Miscellaneous methods including DSS and fuzzy methods account for a share of 20% in energy decision making applications. The number of MCDM applications surveyed upto 1990 is 29% and beyond 1990 is 69% approximately. The methods are observed to be highly popular for renewable energy planning (34%), followed by electric utility planning (19%), energy resource allocation (15%), building energy management (13%) and project planning (12%).

4. Conclusion

A feview of the published literature on sustainable energy planning presented here indicates greater applicability of MCDM methods in changed socio-economic scenario. The methods have been very widely used to take care of multiple, conflicting criteria to arrive at better solutions Increasing popularity and applicability of these methods beyond 1990 indicate a paradigm shift in energy planning approaches. The methods are observed to be most popular in renewable energy planning followed by energy resource allocation. It is observed that Analytical Hierarchy Process is the most popular technique followed by outranking techniques PROMETHEE and ELECTRE. Validation of results with multiple methods, development of interactive decision support systems and application of fuzzy methods to tackle uncertainties in the data is observed in the published literature.

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